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Procedia Engineering 146 (2016) 586 – 593

Procedia Engineering

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8th International Cold Climate HVAC 2015 Conference, CCHVAC 2015

Feasibility Study of a Novel Soil Thermal Recovery Method for HGSHP System

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Abstract

In order to solve the heat accumulation problem of GSHP system in cooling load dominated area with high humidity in summer, this paper presents a novel HGSHP system based on CT cool-storage in transition season. Then the performance evaluation model for HGSHP system is built on the base of the heat and moisture transfer principle of CT, the GHE multiple borehole finite line heat source model and TRNSYS software. At last, using the evaluation model, an actual project in Nanjing is used as an example to predict the thermal performance of this novel HGSHP system. The results show that using novel HGSHP system, the heat accumulation problem can be well solved.

Peer-review under responsibility of the organizing committee of CCHVAC 2015

Keywords: cooling load dominated area; ground-source heat pump; soil heat accumulation; cooling tower cool-storage; feasibility study

1. Introduction

The imbalance of heat extraction from the soil through the ground heat exchangers (GHE) in winter and its rejection into the soil in summer will lead to the “heat accumulation” problem of ground-source heat pump (GSHP) system for cooling load dominated areas [1].Currently, the main method to solve this problem is using hybrid ground-source heat pump (HGSHP), which the cooling tower (CT) is used as supplemental heat rejecter of GHE to undertake part of the condensing load in whole cooling season. For this system, Singh and Foster made a comparison about the technology and economy of two actual projects [2], and presented that the comprehensive technical and economic performance of HGSHP system is apparently higher than GSHP system. Yavuzturk and Spitler studied the

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Peer-review under responsibility of the organizing committee of CCHVAC 2015
doi:10.1016/j.proeng.2016.06.406

control method and gave out the control model of HGSHP system [3], the result showed that in HGSHP system, it is better to operate the CT when the difference between outlet water temperature of GSHP unit and ambient wet bulb temperature. Zhu Lidong simulated different operation modes of hybrid ground source heat pump system, aim at optimizing COP of the system and the annual change of soil temperature. The results show that: paralleling cooling tower and pipe is more conducive to the soil heat balance than in series, for parallel systems, the best control strategy is using 2℃ temperature difference to handle stop/ start of cooling tower with intermittent operation of ground heat exchanger every 2h. In addition, in order to solve soil heat accumulation in cold regions, Yang Tao proposed seasonal soil cool-storage system using natural cooling source. The system uses natural cooling source for cool-storage in winter, ground heat exchanger, intermediate heat exchanger and fan coil for indoor cooling in summer. Yang also predicted the operation effect of different cool-storage modes by simulation. Xie Li proposed a cool-storage mode of cooling tower-ground heat pump coupled in transition season and analyzed the influence of soil average temperature and wet bulb temperature on cool-storage using TRNSYS.

Actually, as an important heat and humidity exchange equipment for air conditioning system, the heat moisture exchange performance of cooling tower is affected by wet bulb temperature t_{S1}, inlet water temperature t_{W1} and water vapor ratio(μ=W/G) etc. These factors will affect or restrict the annual operation of cooling tower. Thus a novel hybrid ground-source heat pump system based on cooling tower cool-storage in transition season is proposed according to the dynamic change characteristic of air conditioning load in hot summer and cold winter area, based on the analysis method and results of the annual operation of cooling tower [4] that presented by our research team (ZL201210103729.2). That is, concerning the thermal performance of CT, during low cooling load period the CT works in parallel with GHE to share the condensing load, and in transition season the CT works in series with GHE to achieve cool-storage into the soil.

In order to validate the feasibility of this method, the performance evaluation model for HGSHP system is built on the base of ground heat exchanger (GHE) multiple borehole finite line heat source model and TRNSYS software. Using this evaluation model, an actual project in Nanjing is chosen to compare the thermal performance of novel HGSHP system and conventional GSHP system. These results can provide reference on high efficiency operation of GSHP system in cooling load dominated area.

2. The novel HGHSP system based on CT cool-storage

2.1. Basic description of the system

The schematic diagram of this new method HGSHP system is given in Fig.1. The basic operation principle is given below: in peak cooling load period (Jul., Aug.), the GHE undertake all the condensing load, and during low cooling load period (Jun., Sep.), the CT work in parallel with GHE to share the condensing load, and in transition season the heat pump system stop working, meanwhile, considering the effect of outside air parameter on the performance of CT, the CT work in series with GHE during this period to achieve the cool-storage into the soil.

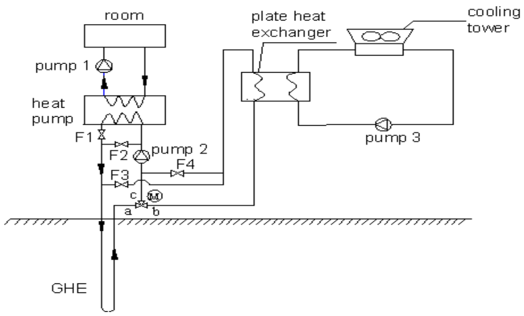

Fig.1. Schematic diagram of novel HGHSP system

2.2. Thermal performance evaluation index

According to this new method, there are two significant parts that will affect the operation performance of HGSHP system. One is the GHE system, another is the CT system. So it is necessary to find the optimal coupling operation condition based on the air conditioning load condition and thermal characteristic of GHE and CT system.

As an important heat and mass transfer equipment for HGSHP system, the heat and mass transfer performance of CT is not only related to structure, material characterization, but also effected by wet bulb temperature of inlet air(t_{S1}),inlet water temperature t_{W1}, water-air ratio(μ=W/G), etc. According to the heat and mass transfer principle, the closer outlet water temperature (t_{W2}) to inlet air wet bulb temperature (t_{S1}), the more sufficient heat and mass transfer process in CT, which will produces a better cooling effect (Fig.2).

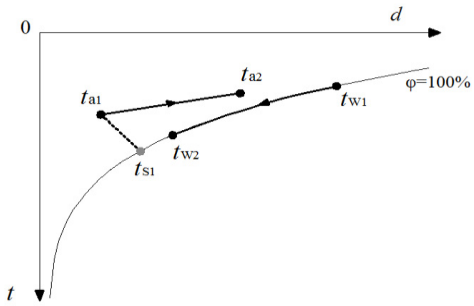

Fig.2. Air - water state change process in h-d chart of CT

In order to evaluate the actual thermal efficiency of CT, two indexes are used. The first is called the relative cooling capacity (β), which means a ratio of actual cooling capacity and rated cooling capacity(Q/Q_0), β is for evaluating the extent to which the actual cooling capacity of the CT close to rated operating condition. The second is called the relative energy efficiency coefficient(ω), which represents a ratio of actual comprehensive energy efficiency coefficient and rated comprehensive energy efficiency coefficient (EER/EER_0), ω is for evaluating the extent to which the actual comprehensive energy efficiency coefficient of the CT close to rated operating condition[7]. Using these indexes, the suitable operation time of a CT chosen as Tab.1 in transition season of Nanjing is given as from Oct. 15th to November 30th and March(Tab.2) [4].

Table 1. Calculation Results of CT Suitable Operation Time in Transition Season of Nanjing

Tine	Inlet temperature(℃)	Outlet temperature(℃)	Soil temperature(℃)	Relative cooling capacity	Temperature difference(℃)
Mar.	19	13.6～15	19.8	0.72～0.81	4.8～5.2
Nov.	24	17～18.7	24	0.94～1.1	5.3～7
Late Oct.	24.2	17.9～19.4	24.2	0.84～0.96	4.8～6.3

The structure and heat transfer process of a single U-tube exchanger can be expressed as Fig.3. There are many factors that have influence on thermal performance of GHE, such as properties and configuration of tubes, thermal parameters of the soil mass(conductivity, thermal capacity, density of soil), and air-condition load characteristic, which of the last is more important in an actual project.

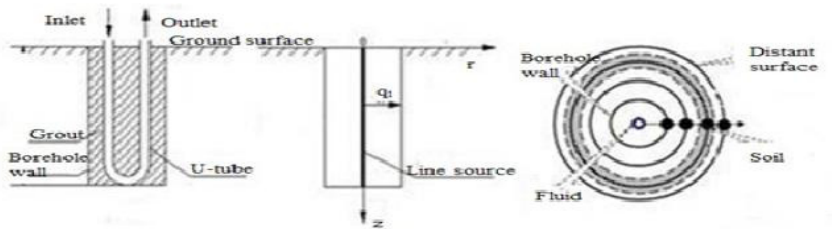

Fig.3. Heat transfer process of GHE

In this paper, the temperature field around multiple boreholes GHE is given as the evaluation index of GHE system. And consuming that the thermal physical parameters of soil mass are constant, the heat transfer process of GHE system meet the superposition principle [5], which can be expressed as Eq. (2). According to the finite line heat source theory of GHE, the excess temperature of any point in soil mass around one borehole is expressed as Eq. (1) [6]. Add Eq. (1) to Eq. (2), the excess temperature response at any point of the soil mass around N boreholes is given as Eq. (3).

$$\theta = \frac{q_l}{4\pi\lambda}\int_0^H \left\{ \frac{\mathrm{erfc}[\frac{\sqrt{r^2+(z-h)^2}}{2\sqrt{\alpha\tau}}]}{\sqrt{r^2+(z-h)^2}} - \frac{\mathrm{erfc}[\frac{\sqrt{r^2+(z+h)^2}}{2\sqrt{\alpha\tau}}]}{\sqrt{r^2+(z+h)^2}} \right\} dh \tag{1}$$

$$\theta_{\mathrm{m}}(\tau) = \sum_{i=1}^{N} \theta_{\mathrm{i}}(\tau) \tag{2}$$

$$\theta(\mathrm{r},\, \mathrm{z},\, \tau) = \frac{1}{4\pi k}\sum_{j=1}^{N} \mathrm{q}\int_0^H \left\{ \frac{efrc\left[\frac{\sqrt{r_j^2+(z-h)^2}}{2\sqrt{\alpha(\tau-\tau_{i-1})}}\right]}{\sqrt{r_j^2+(z-h)^2}} - \frac{efrc\left[\frac{\sqrt{r_j^2+(z+h)^2}}{2\sqrt{\alpha(\tau-\tau_{i-1})}}\right]}{\sqrt{r_j^2+(z+h)^2}} \right\} dh \tag{3}$$

Actually, as the Eq. (3), the q_l are not always constant. Thus, the superposition principle of heat flow is used [7], the basic ideology of superposition principle of heat flow is that a duration heat flow which varies continuously is equivalent to the superposition of many step heat flow. On the base of superposition principle of heat flow, the excess temperature response at any point of soil mass around multiple boreholes under varied continuous heat flow are given as Eq. (4).

$$\theta(\mathrm{r},\, \mathrm{z},\, \tau) = \frac{1}{4\pi k}\sum_{j=1}^{N}\sum_{i=1}^{n}(q_i - q_{i-1})\int_0^H \left\{ \frac{efrc\left[\frac{\sqrt{r_j^2+(z-h)^2}}{2\sqrt{\alpha(\tau-\tau_{i-1})}}\right]}{\sqrt{r_j^2+(z-h)^2}} - \frac{efrc\left[\frac{\sqrt{r_j^2+(z+h)^2}}{2\sqrt{\alpha(\tau-\tau_{i-1})}}\right]}{\sqrt{r_j^2+(z+h)^2}} \right\} dh \tag{4}$$

It can be known that the key point for calculating the temperature response at any point of the soil mass is the q value, which is the heat transfer rate per meter along borehole depth. In this paper, the hourly q value can be calculated as Eq. (5). In this paper, the TRNSYS software is used to simulate the inlet and outlet water temperature and flow rate of GHE, then the q value can be calculated through Eq. (5). At last, put the calculated q value into Eq. (4) the temperature response of the soil mass comes out. In summary, the computational logic diagram of the system performance evaluation model is shown in Figure 4.

$$Mc_p(T_{f2} - T_{f1}) = q_l H \tag{5}$$

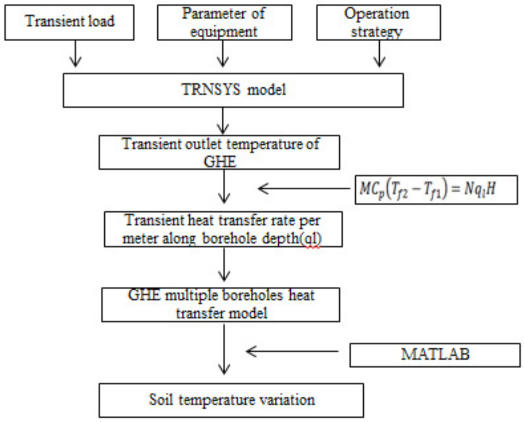

Fig.4. Logical calculation diagram of GSHP performance evaluation model

3. Application analysis

3.1. Project description

A high-rise residential building with 7,000m^2 area located in Nanjing of China is used as the sample building in this paper. The cooling season is from June to September, and heating season is from December to February. The schematic diagram of GSHP system is given as Fig. 5. The single U-tube GHE is used in this project, and the main parameters of GHE and soil mass are given below: the GHE has 1111 boreholes arranged in liner configuration, and each borehole with a depth of 35 m and the borehole spacing is 5 m, and the initial temperature of soil is 18℃; the thermal conductivity of U-tube pipe and backfill material is 0.35W/(m·K) and 1.6W/(m·K); the thermal conductivity of soil mass is 1.5W/(m· K), the density of soil mass is 2804 kg/m^3, and thermal capacity of soil mass is 2579 kJ/(m^3·K).

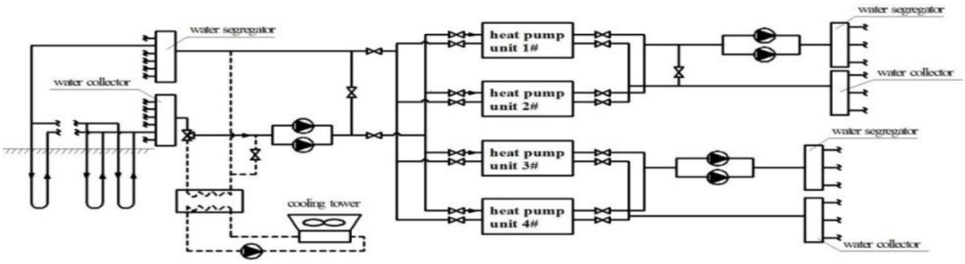

Fig.5. Schematic diagram of GSHP system

According to the analysis of the measured data on GSHP system in 2009, the heat rejected to soil in summer accounts for 68% of the annual total accumulated heat, and the heat extracted from soil in winter accounts for 32% of the annual total accumulated heat. The cumulative cold and heat load ratio which we defined as unbalanced load rate was calculated as 2.09. Especially, as shown in Fig.6, during peak cooling load period in summer of the 3 years, the average inlet/outlet water temperature can be up to 36~38℃/32 ~35℃, which leads to the performance degradation of heat pump.

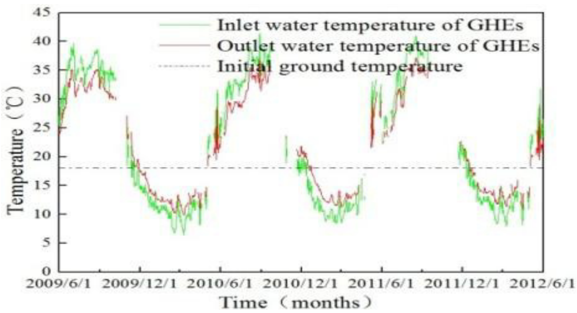

Fig.6. Measurement data of inlet and outlet water temperature of GHE

3.2. System improvement

Using the novel HGSHP system, the schematic diagram of new HGSHP system is shown as Fig.5, which the dotted line part is the adding equipment. And the capacity of added CT has been established, which has a model No. of DBNL3-80, an air volume of 56,000 m^3/h, 80 m^3/h of its water flow rate and the motor power of 2.2 kW. Then the TRNSYS model of GSHP system and novel HGSHP system are built. And Tab. 3 gives out the parameters about main equipment of GSHP system.

Fig. 7 is the schematic diagram of load distribution. Namely, A1 represents the heat rejected into the GHE in summer; A2 represents the heat extracted from soil in winter; A3 represents the heat rejected into the air through CT in low cooing load period in summer; A4 represents the heat removed by the coupling operation combining the CT with GHE in transition seasons. The relationship between 4 parts can be expressed as: A1-A2=A3+A4.

To be clear, the system uses cooling tower to store cold into the ground in late October and November, this partly reduces the soil temperature during winter heating period. It is mainly based on two reasons: First, according to reference 4, the cooling tower is suitable for operation only in March during spring of Nanjing area, this cannot balance the condensation heat in summer that shown in Figure 7 so that the cooling tower needs to work longer; Second, according to the analysis method in 2.2 section, it has little effect on the heating efficiency of ground-source heat pump in winter using cooling tower to store cold into the ground in late October and November.

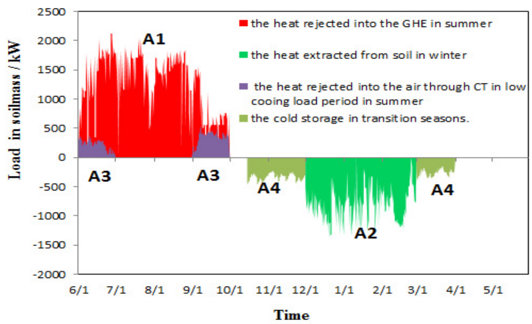

Fig.7. Schematic Diagram of Operation Strategy

Table 3. Main Equipment Parameters of Two Systems

Parameter	Value
Compressor power/kW	240.1(4 units)
Cooling capacity/kW	1070.3(4 units)
Heating capacity/kW	1142.8(4 units)
Flow rate of pump in source side/(m^3 /h)	500

Power of pump in source side /kW	49.2
Flow rate of pump in load side /(m^3 /h)	250
Power of pump in load side /kW	30

4. Result discussion

4.1. Outlet water temperature of GHE

Fig.8 shows the GHE outlet water temperature comparison during 3 years operation. The results show that using GSHP system, the GHE outlet water temperature has the upward trend, the peak value in the third year can reach 35.3℃; while using novel HGSHP system, after 3 years operation, the average value in peak load time can maintain at 29℃. Meanwhile, the outlet water temperature of GHE using novel HGSHP system in heating season can stay at 12℃, which can also maintain high efficiency operation.

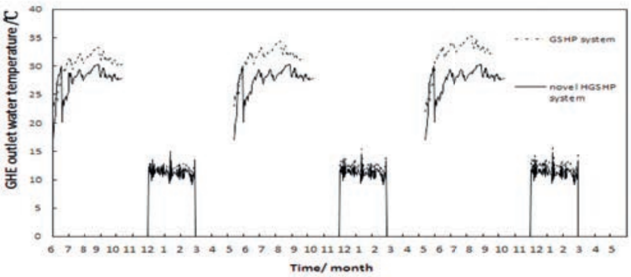

Fig.8.The GHE outlet water temperature comparison

4.2. Temperature field around GHE

Fig.9 is the result of soil mass temperature field at the half the borehole depth plane around 9 GHE boreholes(with 3×3 square configuration) after 3 years. The result shows that, after 3 year's operation using GSHP system, the temperature nearby the 9 boreholes is up to 20.5℃, and the average temperature is about 20 ℃, which is 2 ℃ higher than the initial soil temperature value; while after 3 year's operation using novel HGSHP system, the temperature nearby the 4 corner boreholes turns back to 18℃, and temperature value near the centre area boreholes is also down to 18.3℃, which is only 0.3℃ higher than the initial soil temperature value.

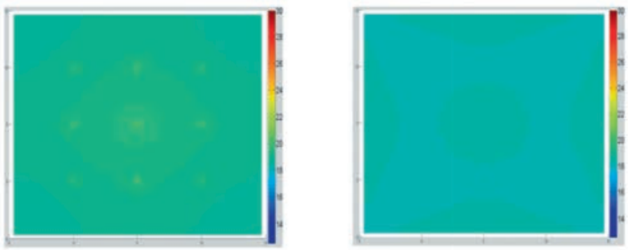

Fig.9.The soil temperature field comparison of (a) GSHP system and (b) novel HGSHP system

4.3. Efficiency of CT

Figure 10 shows the changes in outlet temperature and relative energy efficiency coefficient ω of cooling tower in June, September and transition season. In Figure 10(a), the outlet temperature of cooling tower is generally 25℃, which ensures the heat pump unit work efficiently, in June and September. While relative energy efficiency coefficient ω of cooling tower reaches an average of 0.67 in June and 0.88 in September. In Figure 10(b), the average value of outlet temperature of cooling tower is 15.2℃ in late October and November and 13.9℃ in March. The average value of relative energy efficiency coefficient of cooling tower is 0.52 in late October and November and 0.66 in March.

Overall, it ensures the heat pump unit work efficiently in June and September when the outlet temperature of cooling tower is generally 25℃ and relative energy efficiency coefficient is 0.78. And it helps the cool-storage in transition season when the average value of outlet temperature is 14.7℃ and relative energy efficiency coefficient is 0.57.

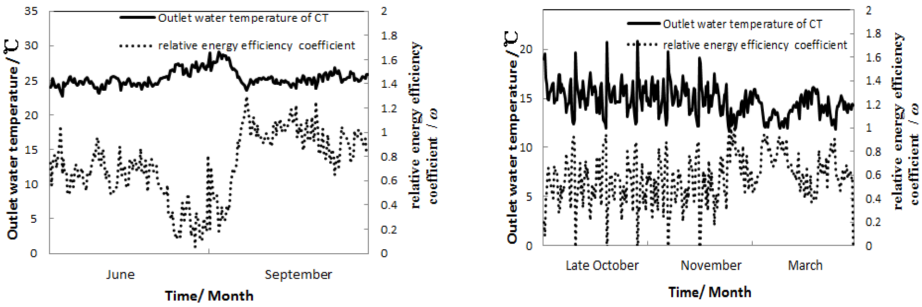

Fig.10. Yearly CT relative efficiency variation in (a) Jun, Sep and (b) transition season

5. CONCLUSION

In order to solve the heat accumulation problem of using GSHP system in cooling load dominated area of southern China, this paper presents a novel HGSHP system based on CT cool-storage in transition season that are more suitable for cooling load dominated area, and the feasibility evaluation model is built on the base of GHE multiple borehole finite line heat source model and TRNSYS software. Then the feasibility of this system is predicted using an actual project. The results show that:

1. Using novel HGSHP system, the outlet water temperature of GHE in cooling season can maintain from 28℃ to 30℃. Meanwhile, its value in heating season can stay at 12℃, which can also maintain high efficiency operation.

2. After 3 years' operation using novel HGSHP system, the temperature nearby the 4 corner boreholes turns back to 18℃, and temperature value near the centre area boreholes is also down to 18.3℃, which is only 0.3℃ higher than the initial soil temperature value.

ACKNOWLEDGEMENT

This project was sponsored by The National Natural Science Fund (50978002).

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